



# Shock-Shock Interaction in the Jet of CTA 102

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**Abstract.** The radio light curve and spectral evolution of the blazar CTA 102 during its 2006 outburst can be rather well explained by the standard shock-in-jet model. The results of a pixel-to-pixel spectral analysis of multi-frequency VLBI images, together with kinematics derived from the MOJAVE survey lead to the picture of an over-pressured jet with respect to the ambient medium. The interaction of a traveling shock wave with a standing one is a possible scenario which could explain the observed spectral behavior.

## 1. Introduction

The blazar CTA 102, (B2230+114), has a redshift of  $z = 1.037$  (Hewitt & Burbidge 1989) and it is classified as a high polarization quasar (HPQ) with a linear optical polarization above 3% (Véron-Cetty & Véron 2003) with an optical magnitude of 17.33. The source was observed for the first time by Harris & Roberts (1960) and right from the beginning it was showing radio variability (e.g., Sholomitskii 1965) which led other scientists to suggest that the signal was coming from an extraterrestrial civilization (Kardashev 1964). Later observations identified CTA 102 as a quasar.

Since that time CTA 102 has been the target for numerous observations at different wavelengths. Besides the mentioned variation in the radio flux density, CTA 102 changes its optical behavior in a no less spectacular way. Pica et al. (1988) reported rapid variation up to 1.14 mag around an average value of 17.66 mag. An increase of 1.04 mag within 2 days in 1978 was so far the most significant outburst. The strongest radio flare since 1986 and a nearly simultaneous outburst in the optical regime took place around 1997 (Tornikoski et al. 1999). Even in the  $\gamma$ -ray regime the source has been detected by the telescopes EGRET on-board *CGRO* and *Fermi* with a luminosity,  $L_\gamma = 5 \times 10^{47}$  erg/s (Nolan et al. 1993; Abdo et al. 2009).

Within the framework of the MOJAVE<sup>1</sup> program (Monitoring of Jets in Active galactic nuclei with VLBA Experiments) CTA 102 has been monitored since mid 1995 (see Lister et al. 2009, and Lister et al. (these proceedings, p. 159)). The results of these intensive observations deliver a detailed picture of the morphology and kinematics of this source. The results of the kinematic analysis show an apparent velocity of the features in the jet between 0.7  $c$

and 15.40  $c$  (Lister et al. 2009). A multi-frequency VLBI study including data at 90 GHz, 43 GHz and 22 GHz was reported by Rantakyrö et al. (2003). The results from the multi-frequency VLBI observations were combined with the continuum monitoring performed at single dish observatories at 22 GHz, 37 GHz, 90 GHz, and 230 GHz. Within this multi-frequency data set (November 1992 until June 1998) CTA 102 showed a major flare around 1997. The authors could conclude that this flare was connected to the ejection of a new jet feature. The inferred apparent speed of 11  $c$ , combined with the frequent and rapid flaring events throughout the electromagnetic spectrum, lead to the picture of a highly relativistic jet. This picture is supported by the conclusions of Jorstad et al. (2005) and Hovatta et al. (2009). They found Lorentz factors,  $\Gamma$ , of 17 and 15, and respectively, Doppler factors,  $\delta$ , between 15 and 22.

In April 2006, CTA 102 underwent a major radio flux outburst and we will present the result of our analysis of this flaring event using single dish and multi-frequency VLBI observations. We found indications that this flaring event was created by the interaction between a re-collimation shock and a traveling shock wave.

## 2. Observations

### 2.1. Single-Dish Light Curves

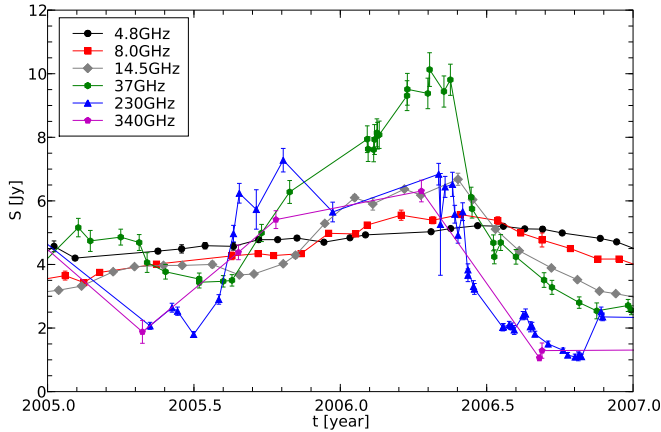
In our analysis we concentrated on the radio flare around April 2006 and used single dish observations spanning from 4.8 GHz to 340 GHz (see Fig. 1). The flare is clearly visible at all the frequencies with increasing time delays towards smaller frequencies. The highest flux density of about 10 Jy is measured at 37 GHz.

A self-absorbed synchrotron spectrum is described by

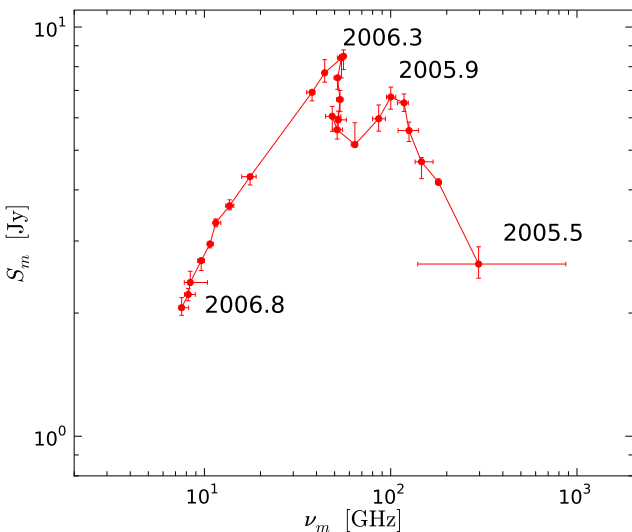
$$S(\nu) = C \left( \frac{\nu}{\nu_1} \right)^{\alpha_t} \left\{ 1 - \exp \left[ - \left( \frac{\nu}{\nu_1} \right)^{\alpha_0 - \alpha_t} \right] \right\}, \quad (1)$$

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<sup>1</sup> <http://www.physics.purdue.edu/MOJAVE>



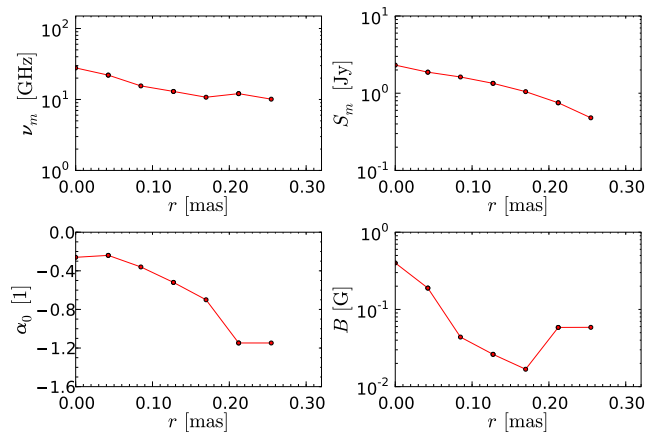
**Fig. 1.** Single dish light curves for CTA 102, centered around the 2006 radio flare. Used telescopes are 4.8–14.5 GHz UMRAO (M. F. Aller and H. D. Aller), 37.0 GHz Metsähovi (A. Lähteenmäki) and 230–340 GHz SMA (M. Gurwell)



**Fig. 2.** The 2006 radio flare in the turnover frequency - turnover flux density plane. The numbers indicate the temporal evolution of the flare.

where  $S(\nu)$  is the flux density,  $\nu_1$  is the frequency at which the opacity  $\tau_s = 1$ , and  $\alpha_t$  and  $\alpha_0$  are the spectral indices for the optically thick and optically thin parts of the spectrum, respectively. The turnover frequency,  $\nu_m$ , and the turnover flux density,  $S_m$ , can be calculated from the first and the second derivative of synchrotron spectrum and they can be regarded as the characteristics of the spectrum.

For the spectral analysis we interpolated the data to a time sampling of  $\Delta t = 0.05$  yr and subtracted an underlying quiescent spectrum. This homogenous spectrum ( $\nu_m = 1.70$  GHz,  $S_m = 4.08$  Jy,  $\alpha_0 = -0.35$  and  $\alpha_t = 5/2$ ) was created from archival data. The spectral evolution of the 2006 radio flare in CTA 102 is presented in the

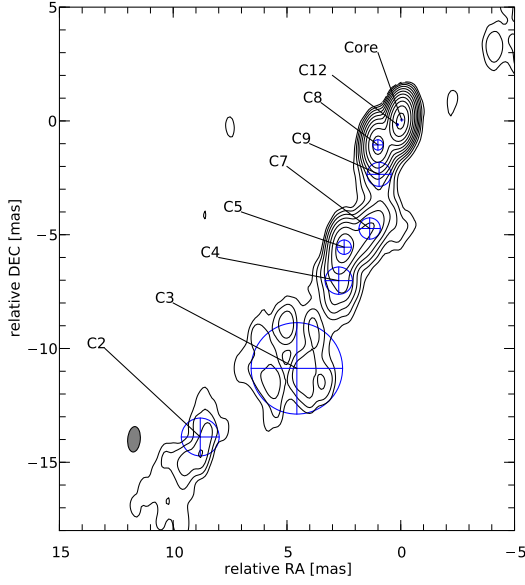


**Fig. 3.** Evolution of the spectral parameters along the jet axis derived from the 2005.39 multi-frequency observations of CTA 102. The estimate of the uncertainties are difficult due their dependence on the image alignment and the uneven uv-coverage between the different frequencies. Note that the individual pixels are not independent. An estimate for the errors, assuming correct alignment, on the turnover frequency and flux density is around 15% of the derived value (see Discussion).

turnover frequency - turnover flux density ( $\nu_m - S_m$ ) plane (see Fig. 2).

The flare starts around 2005.6 at a high turnover frequency ( $\nu_m \sim 300$  GHz) and low turnover flux density ( $S_m \sim 3$  Jy). During the first 0.3 yr the turnover flux density,  $S_m$ , is increasing (to  $S_m \sim 6.5$  Jy) while the turnover frequency,  $\nu_m$  is decreasing (to  $\nu_m \sim 120$  GHz). Following Marscher & Gear (1985) we could identify this stage as the Compton stage, where Compton losses are the dominant energy loss mechanism. The next stage in the shock-in-jet model should be the synchrotron one. This stage is characterized by a less prominent changes in the turnover flux density,  $S_m$ , while the turnover frequency,  $\nu_m$  is still decreasing. One could consider the time between 2005.8 and 2005.9 as a possible candidate for this stage. During this time span of 0.1 yr the turnover flux density is slightly increasing (to  $S_m \sim 7.0$  Jy) while the turnover frequency keeps on decreasing (to  $\nu_m \sim 90$  GHz). In the final stage the energy losses are dominated by the adiabatic expansion of the jet and the relativistic shock, the adiabatic loss stage. During this stage the turnover flux density and the turnover frequency are decreasing. The adiabatic losses start to dominate the spectral evolution between 2005.9 and 2006.0.

The increase of the turnover flux density starting from 2006.0 on and reaching a peak value of  $S_m \sim 8.5$  Jy in 2006.3 can not be explained by the shock-in-jet model. After 2006.3 the turnover flux density decreases with decreasing turnover frequency. A detailed analysis of the single dish observations will be presented elsewhere.

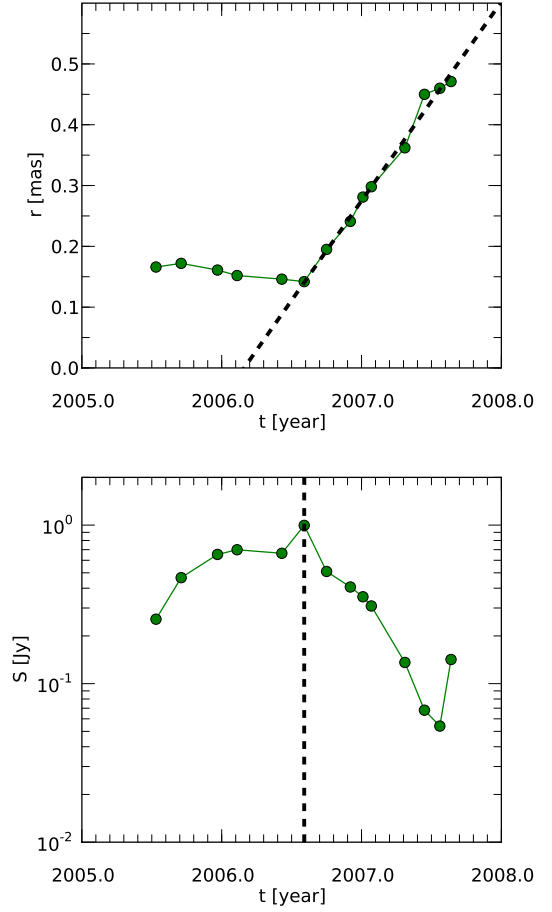


**Fig. 4.** 15 GHz VLBI image of CTA 102 observed on 6th of January 2007.

## 2.2. Multi-Frequency VLBI Observations

Since single-dish observations do not provide structural information of the jet we used as well multi-frequency VLBI observations covering a frequency range from 2 to 86 GHz for accessing the neighborhood of the AGN central engine. CTA 102 was observed with the National Radio Astronomy Observatory's Very Long Baseline Array at three epochs (March 9th 2005, April 14th 2006 and 8th June 2006) using the all 10 antennas of the array. After calibration of the raw data, using the standard AIPS procedures and model fitting in DIFMAP, we performed a core-shift analysis ( $\Delta r \propto \nu^{1/k_r}$ ) following Lobanov (1998) and a spectral analysis on the pixels along the jet axis using Equation 1. From the 2005.39 multi-frequency observations of CTA 102 we concluded from the core-shift results that the source is in equipartition (jet particle energy density equals magnetic field energy density). This circumstance is reflected by a value of  $k_r = 0.98 \pm 0.03$  and leads to an absolute distance from the central object  $r_{\text{core},86\text{ GHz}} = 3.29 \pm 1.12\text{ pc}$  and to a magnetic field  $B_{\text{core},86\text{ GHz}} = 0.40 \pm 0.14\text{ G}$ . From the derived spectral values (especially  $\nu_m$ ,  $S_m$ ) we calculated the magnetic field  $B \propto \nu_m^5 S_m^{-2}$ .

Figure 3 presents the evolution of the physical parameters deduced by our analysis as a function of the distance from the core. The results show an increase in the turnover frequency,  $\nu_m$ , (upper right panel), the optically thin spectral index,  $\alpha_0$ , (lower right panel) and the magnetic field,  $B$ , at a distance of 0.2 mas away from the core. This behavior could be an indication for an re-collimation shock (standing shock wave) at this position.



**Fig. 5.** Properties of the C12 component from the MOJAVE observations. Left: Separation from the core inclusive linear fit to the acceleration event (dashed line). Right: Evolution of the flux density and time of beginning of the acceleration event (dashed line, see text for explanation). The uncertainties for the flux densities are around 5% of the total intensities and the positional errors are of 1/5 of the restoring beam dimensions (typically around 0.01 mas)

## 2.3. MOJAVE Observations

To check the evidence for a re-collimation shock at a distance of 0.2 mas from the core we used the kinematic analysis of the 15 GHz VLBI monitoring of CTA 102 (Lister et al. 2009). A high resolution VLBI image of CTA 102 observed at 15 GHz on January 2007, showing the location and size all fitted circular Gaussian components, is presented in Fig. 4. The kinematics and the evolution of the flux density of a fitted component labeled as C12 could be interpreted as the interaction of a moving shock wave with the re-collimation shock: the separation from the core ( $r \sim 0.2\text{ mas}$ ) remains constant until mid 2006, when an acceleration event takes place together with a sharp drop in the flux density (see Fig. 5).

By fitting the acceleration part of the C12 trajectory and correcting for the core-shift we derived a value for the ejection time,  $t_{\text{ej}} = 2005.83 \pm 0.05\text{ yr}$ . This time cor-

responds to the first peak in the  $\nu_m$ - $S_m$  plane. The second peak is located slightly before the time of the beginning of the acceleration event (possible intersection of the moving shock wave with the re-collimation shock)  $t_{\text{intersec}} \sim 2006.6$  yr. Using a viewing angle of  $\vartheta = 2.6 \pm 0.5^\circ$  (Jorstad et al. 2005) we derived a velocity  $\beta = v/c = 0.998 \pm 0.042$  and a bulk Lorentz factor  $\Gamma = 17.7 \pm 0.7$ .

### 3. Discussion

The evolution of the 2006 radio flare in the  $\nu_m$ - $S_m$  plane could be explained by the interaction of a moving shock wave with a re-collimation shock. Re-collimation shocks are stationary features in non-pressure matched jets and lead to local increase in pressure and change in the orientation and value of the magnetic field (Daly & Marscher 1988; Falle 1991; Perucho & Martí 2007). This behavior can be seen in the increase of the turnover frequency,  $\nu_m$  and the increase in the magnetic field,  $B$  at a distance of 0.2 mas in the evolution of the spectral parameters derived from multi-frequency VLBI observations (see Fig. 3). The first peak in the  $\nu_m$ - $S_m$  plane corresponds to the ejection of the traveling shock wave around  $t_{\text{ej}} \sim 2005.85$  yr. The trajectory of this new feature can not be observed at 15 GHz due to the limited resolution. The interaction of the moving shock wave with re-collimation shock takes place around mid 2006 which could lead to the second peak in the  $\nu_m$ - $S_m$  due to shock acceleration in a region of increased pressure and magnetic field. During the interaction of the two waves the re-collimation shock is pulled away by the moving one and should appear after some time again at the same position. One possible explanation why this reaction is not detected in the 15 GHz kinematics could be a rarefaction wave. This wave is traveling in the wake of the moving shock wave and decreases the pressure behind the shock front. Together with the limited dynamical range of the VLBI this could be the reason for the non-detection of the re-collimation shock after the collision with the traveling one.

### 4. Conclusions and Outlook

The combination of single-dish observations with multi-frequency, densely time-sampled VLBI monitoring is a powerful approach which can contribute towards a better understanding of flaring events. Using a high-quality set of observational data we presented a possible scenario which could explain the observed flare by a shock-shock interaction and derived estimates for the physical parameters of the jet and the traveling shock wave.

The spectral values presented have been derived from a spectral analysis applied on multi-frequency VLBI observations. This technique is sensitive to the correct image alignment and to effects of the uneven uv-coverage between the frequencies. The effect on the derived parameters due to small misalignments could lead to significant changes in the spectral values, especially in the magnetic field ( $B \propto \nu_m^5 S_m^2$ ). Further analysis of the influence of the

alignment is needed to provide adequate error bars for the derived values.

Besides quantifying the uncertainties on the observational parameters we started to test our assumption of the shock-shock interaction using 2D relativistic magnetohydrodynamic simulations. These simulations will help us to understand the formation of re-collimation shocks in magnetized jets and their interactions with traveling shocks.

It is also of interest to investigate possible correlations between  $\gamma$ -ray flares and the collision of re-collimation shocks and traveling shock waves. These investigations could help to clarify the question where in the jet the high energy radiation is generated.

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